System Concepts and Technologies for High Orbit SAR (Invited)

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***Abstract* — This paper discusses large aperture, high orbit radar concepts for measuring sub-centimeter-level surface displacements from space. These measurements will enable applications such as earthquake simulation, modeling and forecasting. We will explain the need for large aperture, high orbit arrays and will discuss the technologies required to achieve these missions.**

***Index Terms* — active arrays, phased array radar, radar, synthetic aperture radar.**

I. INTRODUCTION

National Aeronautics and Space Administration (NASA) has identified an Interferometric Synthetic Aperture Radar (InSAR) mission in L-band as one of its highest priorities [1]. Such an orbital InSAR system will enable continuous sub-centimeter-scale vector measurements of surface displacement over wide areas and will enable measurements of the dynamics of the Earth's crust, ice sheet motion, and other surface change measurements [2]. Observations of such phenomena with existing Synthetic Aperture Radar (SAR) sensors have shown the power of the interferometric technique, leading to exciting possibilities with future, more capable, systems. This is illustrated in Fig. 1, showing wide area observations of the large 1997 Manyi earthquake, made with an existing 35 day repeat SAR system, the European ERS-2 radar satellite. The interferometric observations were laboriously stitched together from observations made at six different times, leading to an impressive but limited snapshot of the surface deformation that occurred from before to after the event. In this case, there is an incomplete picture of the events leading up to the earthquake and how the crust responded to it over time. While current and planned sensors will have repeat periods on the order of one or more months, current science goals call for repeat periods of as little as one day. Improvements in temporal sampling of evolving surface phenomena are integral to the long-term vision for Earth system research. This vision would extend the results in Fig. 1 from a static depiction of two moments in the evolution of the crust to a complete time history of the straining crust leading up to the event and through its post-seismic relaxation. These would be essential observations for modeling and eventually prediction of earthquakes. Access to higher orbital vantage points is an attractive way to obtain more continuous observations in both space and time because as spatial coverage increases, the spacecraft orbits can be tailored to repeat more frequently, thereby improving the temporal sampling as well. In the next section we will show how a high orbit sensor in Medium Earth Orbit (MEO) can provide the desired repeat times for the applications discussed here providing a vastly improved monitoring capability.

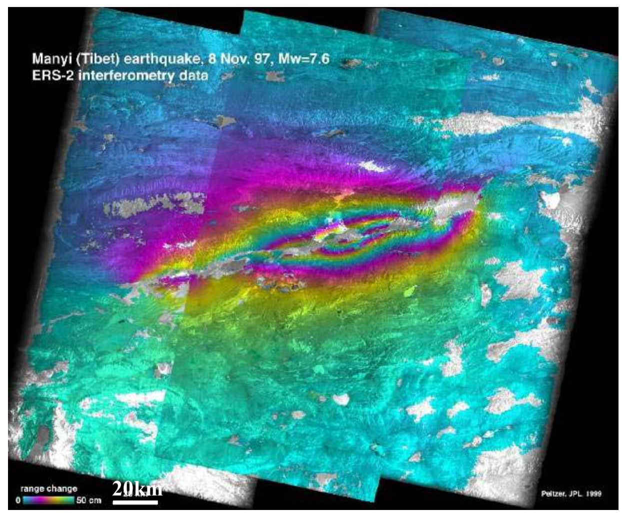

Fig. 1. Signature of Manyi Mw=7.1 earthquake. The color indicates relative displacement of the surface well over 1 meter from before to after the earthquake. This earthquake covered such a great extent that it was necessary to mosaic three adjacent tracks of repeat pass interferometric data [3].

In addition to the Earth science applications discussed above, radar measurements are also gaining increased relevance in planetary science. Radar measurements can also be used to probe below the surface. Planetary SAR missions with the potential for breakthrough understanding of Mars' ice cap dynamics (flow, precipitation, and sub-ice melting), temporal variations of Europa's crust (i.e., characteristics of a sub-crustal liquid water ocean), and the surface deformation and/or volcanic activity of other planets (i.e., active hydrothermal or geothermal systems on Venus, Mars, etc.) are possible. All of these objectives are, at least in part, tied to the search for past or present life within the Universe, and as such are a major component of the NASA Vision. Technologies that reduce mass and volume are key to reducing cost and enabling these missions.

II. Orbit Selection

Orbit selection is perhaps the most defining step in the architectural design of an InSAR observing system, and because the image resolution of a SAR sensor can be made nearly independent of range, Earth coverage is probably the most relevant performance metric in the selection of an appropriate orbit. Greater coverage implies shorter revisit times and thus higher temporal resolution and more extensive data sets of target areas.

A first-order estimate of a SAR sensor's cumulative accessibility is given by its coverage rate, which can be modeled as the product of the platform velocity and the width of the SAR accessible swath [4, 5]. Fig. 2 shows the coverage rate as a function of platform altitude. Because the nadir velocity decreases with altitude while the swath width increases, these curves peak at around 3000km altitude. A single MEO sensor at 3000km altitude could provide a two-day repeat period while maintaining global coverage; a constellation of four such spacecraft could provide an effective interferometric repeat period of six hours [4, 5].

As science models improve to the point that specific target areas on the Earth are to be monitored continuously, a pair of Geosynchronous Earth Orbit (GEO) SAR sensors could provide truly continuous coverage of such sites. In this mode of operation, the instantaneous accessibility of the sensor (i.e., the sensor field of regard) is a more indicative measure of performance than the cumulative accessibility (Fig. 2). Due to the large footprints of higher orbits, orbits at 10,000 to 40,000km altitude would be most effective for providing continuous or near continuous coverage of targeted areas. Since current requirements for solid-Earth science call for revisit periods of hours to days rather than around-the-clock coverage, however, a 3000km orbit may be most suitable for near-term measurement objectives. [2, 5, 8]

To effectively use the accessibility provided by a high vantage point, we require very large antennas with electronically steered beams. Fig. 3 illustrates the ideal minimum antenna area as a function of platform altitude for various maximum ground incidence angles [4, 5]. The antenna size for a geosynchronous SAR is on the order of 700m^2 for the lower incidence angles as compared to antenna areas of roughly 50m^2 required for Low Earth Orbit (LEO) systems. MEO SAR altitudes require antenna areas of roughly 400m^2.

Another important consideration in selecting the orbit is the radiation environment. The radiation environment varies significantly for different orbit altitudes and inclinations. For instance radiation is known to be particularly severe at MEO and it would undoubtedly drive the design and technology selection. In addition, higher altitudes require greater transmit power, while lower altitudes have more demanding antenna steering requirements.

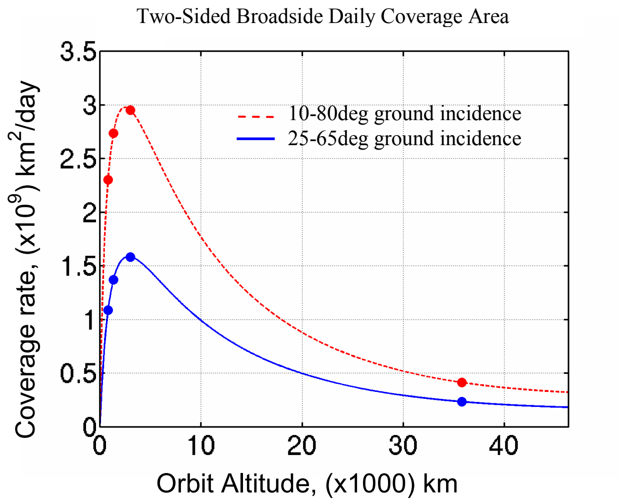

Fig. 2. Coverage rates as a function of orbit altitude for swaths limited by ground incidence angle. Markers correspond to 800km (Low Earth Orbit or LEO), 1300km (high LEO), 3000km (MEO), and 35,800km (Geosynchronous) altitudes.

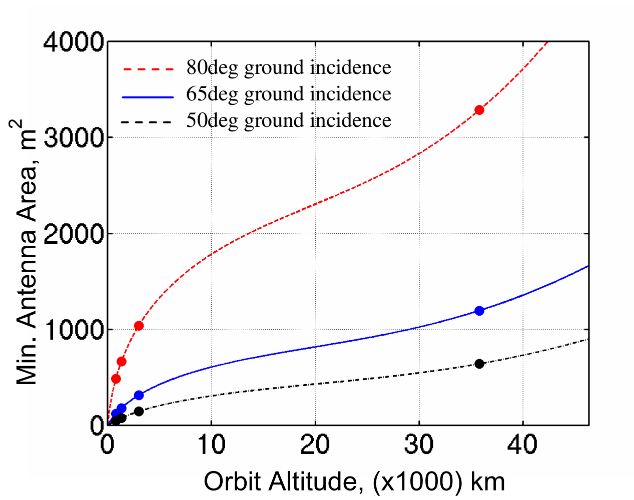

Fig. 3. Required L-band antenna area vs. orbit altitude for assumed far-range ground incidence angles (markers are for 800, 1300, 3000, and 35,800 km altitudes).

III. Technology Needs

Along with their advantages, the high orbit SAR architectures described above also involve serious technological challenges. First, and perhaps foremost, we require revolutionary antenna technologies to enable these increasingly large tantenna systems. These large active antennas would be a challenge to build, deploy, and maintain.

It is estimated that we need antennas with mass densities of 2 to 4 kg/m^2 to enable the large-aperture SARs of the previous section to be lifted into space using available launch vehicles

[5] (for comparison, the phased array used in the Shuttle Radar Topography Mission had a mass density of more than 20 kg/m^2). These mass densities include the antenna support structure, the aperture, and all antenna-mounted electronics. One approach for achieving the necessary order-of-magnitude reduction in mass density is the use of thin film membrane material for the antenna aperture, along with lower-mass support structures [6, 7]. Fig. 4 shows a passive membrane antenna developed at JPL. More recently we have demonstrated a prototype active membrane antenna [8] with integrated Transmit/Receive (T/R) modules. A membrane antenna is not only lightweight but it also allows large antennas to be stowed by rolling and/or folding, reducing the stow volume of the antenna. The mass, complexity, and cost of rigid manifold and membrane-based systems need to be weighed against the resulting performance. In the short term, a membrane-based antenna with more structural support could be an acceptable solution, with more mechanically flexible systems following as the technology matures. Below are some of technologies that need to be investigated to enable a low-cost, large aperture antenna for future SAR applications. For a more complete list see [4] and [5]. We assume a membrane-based antenna, although as discussed above, the level of the mechanical flexibility of the membrane antenna needs to be further studied.

Fig. 4. JPL's 1x3m passive membrane antenna. The top figure shows the antenna in stowed configuration. The antenna is partially deployed in the middle and fully deployed in the bottom figure [6,7].

Advanced radar Electronics

Some examples of advanced electronic technologies for large membrane antennas are:

High Efficiency, radiation-hard, integrated MMIC T/R modules: T/R modules are one of the most critical components of a phased array. Since the ultimate goal is to keep the mass and stowed size of the antenna small, conventionally packaged T/R electronics are not appropriate. It is desirable to integrate all the electronics onto a single chip and deal with the pick and placement of only one chip per unit cell. High-efficiency T/R modules would reduce power requirements and improve the thermal management of the array [9]. Current candidates for L-band are GaAs and Si. The radiation tolerance of GaAs needs to be weighed against the better thermal characteristics, lower cost and robustness of thinned flex-Si. Current SOI CMOS technology might be a good alternative to GaAs. More work in this area needs to be done to assess the feasibility of a fully integrated Si T/R module.

True Time Delay (TTD) Components: Because of the large size and operating bandwidth of the antenna, true time delays are required for proper beam formation. It is impractical to apply a true time delay to each array element; instead we can divide the array into sub-arrays and apply a true time delay to each sub-array. This could be achieved in analog circuitry, using electrical or optical delays, or in digital circuitry.

Power tiles: A power tile is a combination of a solar cell and battery that powers a phased array. We need high efficiency and membrane-compatible power tiles for integrated and distributed power generation and storage on large aperture membrane antennas.

Flexible large area electronics (macroelectronics): Using amorphous, low temperature polysilicon, and various organic and inorganic nanocrystalline semiconductor materials is beginning to show great promise for direct fabrication of electronics on large rigid and flexible material [10]. The direct fabrication of electronics on membrane materials could replace integration of conventional electronics (discussed below) with membrane antennas. While much of the activity in macroelectronics has been display centric, a number of technologies are showing promise for use in radar applications.

Integration of Electronics

In addition to the need for new technologies for the antenna structure, aperture and the electronics, the reliable integration of these electronics with a large aperture would also require innovative technologies. This is especially true for flexible membrane antennas where the electronics need to be integrated with a thin film membrane. The attachment and/or embedding of a die onto the membrane and its reliability is a challenge. We need to improve technologies such as flip-chip on flex and develop new technologies such as embedding of electronics inside the thin membrane for added reliability [11]. To integrate passive components onto the membrane structures we can use embedded or integrated passives.

Antenna System Integration

Just as new technologies would be required for integrating the antenna electronics with the aperture, the integration of the entire system requires new technologies as well. Examples of these technologies are:

Metrology and calibration: SAR measurements require the precise knowledge of the phase of the signals received. This requires the knowledge of the position of the antenna, phase of the electronics, etc. Metrology and calibration are more complicated for a large antenna, especially if it lacks mechanical rigidity. Membrane antennas differ from standard, rigid phased-arrays in that physical displacement may be a significant contributor to phase-front error and can be rapidly changing temporally and spatially. Therefore, it is essential to develop a new metrology and calibration (adaptive aperture control) system for membrane-based antennas without a rigid support.

Interconnect technology: We need new architectures and interconnect technologies to simplify the connection of thousands of unit cells on a large array. This includes RF, DC, and digital signal distribution. Conventional cabling for large apertures with thousands of T/R modules is very complicated and adds mass to the antenna. Possible solutions are optical and wireless signal distribution.

Passive and active thermal management: Thermal management of a large array is critical for radar performance and is more challenging for a membrane array due to low thermal conductivity of the material used. New technologies such as radar transparent thermal control coatings, variable emissivity surfaces/coatings, integrated phase change thermal storage, and mini/micro heat pipes can be used for adaptable thermal control. Eventually, active techniques such as capillary loops or mechanically pumped loops, micro-channel heat sinks, micro loop heat pipes, and micro heat pumps can be developed.

Manufacturability: Techniques such as roll to roll processing might assist in the manufacturing of future very large arrays. We need to consider issues such as testing and reworkability of components on a large array to obtain a reliable, low-cost final product.

IV. Conclusions

InSAR is an important technique to improve understanding of earthquakes and other natural hazards and may one day provide the capability to forecast or predict earthquakes. The orbit geometry is a key parameter to improving temporal coverage, and a constellation of MEO InSAR systems will further increase accessibility to the point that nearly continuous monitoring of earthquake phenomena is achievable. Mission system studies have determined that existing lightweight antenna technologies will not meet the mass and cost goals needed to make these systems practical. Therefore membrane antennas and technologies compatible with these antennas are of interest.

Acknowledgement

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